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THE IMPACT OF SPACE TECHNOLOGY ON RESEARCH AND DEVELOPMENT - STRUCTURES AND MATERIALS

By

Richard V. Rhode
Washington, D. C., U. S. A.

and

John C. Houbolt Wash D.C. NASA, [1958]
Langley Research Center
Langley Field, Va., U. S. A.

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combination with maximum aerodynamic loads, resulting in loading conditions which are more critical than either source of loading alone. It would appear that the flat-type trajectory should be avoided since q's as high as 4,000 psf are indicated; this type trajectory may be desirable for other reasons, however, such as a safe abort trajectory.

In contrast to exit, maximum temperatures and q during reentry occur simultaneously at high altitudes; severe loading combinations are thus also present during reentry. The q's are generally much lower than during exit, but the temperatures may be appreciably higher, and in the example shown reach a maximum of 2,000° F.

The temperature curves indicated on figure 4 are for a fixed angle of attack and a fixed value of emissivity; these values have an important bearing on the equilibrium temperature reached, however. Figure 5 illustrates this point and is based on the consideration of various reentry flights having different maximum values of q; in the figure, the maximum equilibrium temperatures reached during the flights are shown as a function of the maximum q attained, and curves are given for several values of angle of attack and emissivity. For a given q, it is seen that rather sizable changes in equilibrium temperature can result from the use of a different ϵ or α. Thus, the emissivity characteristics of the structure and the control of angle of attack have an important role in determining the severity of the temperature problem during reentry.

It is worthwhile to point out that the temperature values indicated on figures 1, 4, and 5 are all based on laminar-flow considerations and are for a point on the structure 1 foot behind the leading edge. The temperature variation along the surface, however, is such that the temperatures decrease behind this point and increase ahead of it, becoming a maximum at the leading edge, where the heat-transfer coefficient is the largest. The temperatures at the leading edge may, in fact, be several times as great as the temperatures indicated on the figures; hence, the leading edge will be a very critical item in structural design consideration.

The dynamic pressures, heating, and decelerations which a given vehicle experiences during reentry are heavily dependent upon the L/D ratio and the angle which the flight path makes with the atmosphere during the initial part of reentry. Small deviations from the planned reentry angles, for example, may seriously alter the anticipated pressure and heat loadings. Thus, these factors need to be considered in study of loads on space vehicles. Figure 6 presents the results of a specific study and shows the maximum deceleration experienced as a function of L/D and reentry angle. These results show that in the range of L/D = 0, small changes in either the reentry angle or L/D can lead to large changes in maximum decelerations. In contrast, for large L/D, changes in L/D or in reentry angle lead to relatively small changes in deceleration. Thus, deviations from planned reentry angle or L/D ratio should be considered in assessing the loadings on space vehicles.

Deviations in pressures and temperatures from planned conditions do not have to result necessarily from trajectory changes alone, but may arise also from changes in the environment, as for example, changes in the temperature and density of the atmosphere due to diurnal or seasonal trends, or due to a change in geographic position. Recent IGY atmospheric soundings show that there may be at least a 20 percent variation in density in going from one latitude to another, and that a like variation may even occur in successive days. These variations, while perhaps not causing a sizable change in the instantaneous pressure loading, have a rather important bearing on the complete flight path of a vehicle, and can in many cases cause the deviations from a planned trajectory to be greater than that desired. A thorough survey and understanding of atmospheric variations is therefore needed.

Load distribution a major problem area.- Knowledge of the load distribution is of course essential for the rational design of structures. For space-type craft this represents a rather large area of ignorance due to the new configurations that must be considered and because the range of operation is beyond the applicability of existing theories or the capabilities of existing experimental facilities. The hypersonic flow region is of particular interest. Indications are that unusual flow phenomena may occur, which may depend on such items as leading-edge contour, or the extent and nature of boundary-layer development and its dependence on angle of attack. Load distribution will also depend strongly on shock wave interaction, which is difficult to assess because it depends primarily on the configuration. Thus, in addition to evaluating the severity and consequence of the various load sources, much research is needed in establishing the detailed nature of the loads so that efficient structural design may be achieved.

Dynamic Loads

The preceding discussion has dealt primarily with near steady or "Quasi-static" loads. Of equal importance in the successful operation of spacecraft are time-dependent loading problems.

Vibration and flutter.- Vibration and flutter problems are representative of a large class of dynamical problems certain to be of importance. "Flutter" is used in the classical meaning of aerodynamic feedback to create a dynamical instability and also in the broader sense of feedback of other kinds of energy associated with the system and its environment. Vibration is used in the sense of structurally transmitted oscillations and airborne induced oscillations as by noise. Despite radically new configurations and concepts, many of the old aeroelastic problems are still present. Antiballistic missile systems will operate at high dynamic pressures and classical coupled flutter for supersonic and hypersonic speeds will remain a design problem, regardless of whether control bodies or wings are in external or internal flows. For very lightly loaded surface structures using skin or sandwich panels, panel flutter will be a problem. Long slender bodies and canard surfaces or all-movable control surfaces in boost-glide type vehicles will also introduce aeroelastic problems such as divergence and structural feedback from elastic modes.

A representative list of these and other vibration and flutter problem areas that are expected to exist for space vehicles follows:

a. Vibration and noise.

b. Interaction of structural vibration with control and guidance systems.

c. Lifting-surface flutter on models having aerodynamic stability.

d. Panel flutter.

e. Effect of high-temperature operation.

f. Flutter at extreme angles of attack during reentry.

g. Effect of high forward acceleration on flutter.

h. Reduction of stiffness due to meteorite erosion.

i. Fuel sloshing interaction.

j. Nonlinear phenomena (e.g., dynamics of structures with buckled members).

Not all these problems can be discussed in detail, but a few comments will be made about a selected few to indicate that each may have a rather wide scope in itself. As an example, consider vibration and noise. Some of the prime sources of energy for exciting vibration and noise are: (a) rocket engine and auxiliaries, (b) boundary layer, (c) buffet and flow separations and wakes, and (d) atmospheric turbulence. To indicate the range of problems covered by these energy sources, it is convenient to consider the frequency of excitation, which is particularly important in determining the class of problems affected. At low frequencies below 20 cps, the vibration problems are primarily those of (1) "smokestack" oscillations due to shed vortices, (2) structural feedback in control systems, (3) fuel sloshing, and (4) vibration fatigue in man. Between

20 and 1,000 cps, both noise and vibration lead to such problems as (1) hearing impairment, (2) malfunction of electronic equipment and accessories, and (3) local failures of skin panels. Above 1,000 cps the detrimental effects are largely those of noise on hearing, since this is the range above most significant structural frequencies but in the range of maximum sensitivity of the ear. Certain small electronic components are also adversely affected in this range.

Another example is that of the problem of flutter as related to high-temperature operation (item e). The flutter problem may be aggravated because of a loss in stiffness due to:

a. Buckling due to thermal stresses,

b. Loss of elastic modulus,

c. Design procedures which break up the skin into small elements to prevent thermal buckling,

or it may be aggravated because of the considerable weight which may have to be added for insulation or cooling purposes.

Another factor that must be considered and which will likely make transonic and low supersonic flutter critical in design consideration is the launching problem. A vehicle that is designed for efficient operation at a dynamic pressure of less than 100 psf must survive dynamic pressures possibly in excess of 1,000 psf during launch. The problems that one may encounter might be similar to those one would experience if he attempted to fly a light sport plane at transonic speeds.

These are some things that will make flutter and vibration a major design consideration in space vehicles. A rather sizable Mach number range is covered by these problems, and to indicate the Mach number range that is likely to be important for some of the problems, figure 7 has been prepared. Whether some of the problems will be critical at hypersonic speeds and at extreme temperature conditions, or at transonic speeds will have to be determined for each configuration. But to do this, much research is needed in the relatively unexplored hypersonic speed range to help define the problem and to determine components which will have the best flutter margins.

Transient loads.- As with aircraft, transient load problems will also have an important bearing on the design and operation of spacecraft. Some will be similar in nature, while others will be new because of the nature of the configuration or its mission. No sharp dividing line can be given certain of the transient loads phenomena because of obvious overlapping with some of the vibration problems discussed in the preceding section. However, to give an indication of transient loads problems that are already known to be of concern, the following listing is given:

1. Gust loads associated with atmospheric turbulence and wind shear.

2. Transients caused by "hard-over" gimballing of rocket motors.

3. Separation dynamics.

4. Meteor impact.

5. Loads developed during rendezvous operation.

6. Landing impact.

While a certain amount of information exists on some of these problems, most of them are relatively new and require research attention to define their severity. As regards gust loads, much information has been gathered for aircraft in horizontal flight, but relatively little information exists on the gust fields and wind shears that are associated with flight in a near vertical direction. The "hard-over" gimballing of rocket motors has already had to be considered in the design of some satellite vehicles. Separation dynamics may pose special problems for some configurations, and may be especially important in the case of an aborted mission. Meteor and rendezvous impact problems represent major unknown areas, and, as mentioned previously, the landing problem will be very severe and will require the development and evaluation of new procedures.

DETAILS OF THE STRUCTURAL CONFIGURATION

As noted earlier, the trend of structural development over the past two decades has been toward structures of increasing density. Ultimate design stresses have increased and more efficient structural designs have been developed. In the later part of this period, aerodynamic heating has forced changes in structural geometry to reduce thermal stresses, and in the more advanced cases, materials of construction have had to be changed and special measures for insulating and cooling have had to be considered.

The trend is expected to continue for many applications, but structures of very low density now also have to be given much attention. The thin-wall construction of liquid-fueled rockets is an example. The potentialities lying above the present upper limit of the "flight corridor" should be exploited. Finally, for pure space applications with no aerodynamic forces present, low-density pressurized structures have already attracted some attention.

Knowledge on aircraft structural development applicable to space vehicles.- Since flight into and back from space must of necessity be in part within the atmosphere, astronautical engineering should draw heavily on aeronautical engineering developments. As pointed out in the introduction, no sharp dividing line between the two can be drawn - indeed, the hypersonic aircraft can become an orbiting vehicle.

For some vehicles and missions - for instance, booster rockets of the liquid fuel type - the structure involved does not differ radically from present or near-future aircraft structures, and the temperatures are in the range where conventional materials can be used - aluminum alloys, titanium, and conventional steels. A fair amount of knowledge on the stiffness and strength of structures at elevated temperatures has been acquired, but additional knowledge is needed, especially for structures of low density. It would, therefore, be greatly desirable to correlate and condense the knowledge available in this field to facilitate design procedures.

For space vehicle design, one guiding principle is emphasized even more than in aeronautical design: to keep weights low. This fact becomes strikingly clear when cognizance is taken of the fact that under the present state of rocket development, it takes from 200-1,000 pounds of initial weight to put 1 pound in orbit. The severity of the problem becomes evident when it is realized that much structurally useless material may have to be carried along to provide heat and radiation protection for manned vehicles, and further that the questions of reliability enter much more than ever before because of the lower density structures that may be involved.

Four basic types of construction involved.- In the design of a heat resistant structure, separate consideration will usually have to be given the surface areas and the leading edges. For the surface areas there are basically four types of construction that lead to a heat resistant structure and these are depicted in figure 8. One approach is that of an unprotected structure represented by a sandwich skin of high-temperature material. Structural temperature in this case is governed mainly by the ability of the structure to radiate away much of the incoming heat that is developed by convective boundary-layer heating; the heat capacity of the skin enters only in a secondary manner. Considerable work has been done on the development of this type structure and it is of interest to note that, in marked contrast to previous design experience, there are now instances of low-aspect-ratio wings where the structural engineer can provide a thinner lifting surface than required for aerodynamic reasons, at a saving in weight.

The remaining approaches are basically methods to either block or absorb a portion of the heat input to limit temperature rise. One of these approaches involves the use of an insulated or "heterogeneous" structure in which the inner load-carrying structure is kept cool by an insulation which, in turn, is kept in place by a heat-resistant (radiation) outer shell.

Another scheme, the heat sink, involves simply the use of a thicker structural skin in order to obtain the desired heat capacity to absorb heat. In this case, the heat capacity of the structure can be raised by the incorporation of materials of high specific heat, such as beryllium, or by the addition of a coolant, such as water.

The fourth approach, which is known as ablation, makes use of an external layer of material which absorbs heat as it is consumed; alternate schemes for this case may involve sweat (evaporation) cooling.

The unprotected and insulated approaches are best suited for continuous flight application, and therefore seem most appropriate for manned reentry considerations. The heat sink and ablation approaches apply mainly to those cases in which there is a very high influx of short duration and these approaches therefore appear naturally best for ballistic-type reentry.

There are also four basic schemes for use in leading edge design, see figure 9. As with the surface structure, either the heat sink or ablation principles may be used, or as alternatives, the leading edge may be given a protective coating of refractory material, or it may be kept cool through means of mechanical cooling devices. These cooling schemes may involve either the use of a circulating coolant or the use of a gas or fluid which is ejected through slots.

Although certain concepts of construction seem quite clear, additional research is needed to provide guide lines to help the structural designer in selecting the most efficient structural approach for the mission of his particular vehicle.

<u>Structural analysis methods require extension to low-density type structures</u>.- The trend toward low-density type structures for space vehicles seems clear, and to give an idea of the resulting structural problems that require increased attention, the following four problem areas are cited:

1. Buckling strength of very thin shells.

2. Prediction of failure modes and general instabilities.

3. The determination of temperature distribution, thermal stresses, and thermal deformations.

4. Efficient design of structural joints.

The buckling strength of thin shells is strongly influenced by initial imperfections; consequently, the buckling theories for such shells always had to be modified by empirical reduction factors. Recent studies have, however, demonstrated the beneficial effect that may be achieved by internal pressurization; figure 10 illustrates the case in point. Here the coefficient for local buckling of a cylinder under axial compressive load is plotted against a parameter involving the internal pressure p, the elastic modulus E, and the ratio R/t of cylinder radiu to skin thickness. The zero pressure buckling coefficient corresponds to the value usually found in cylinder tests. An increase in internal pressure is seen to cause the local buckling coefficient to increase until the theoretical value of 0.6 for a perfect cylinder is reached - thereafter, no increase in buckling stress is noted. This realization of the full potential load-carrying capabilities of a shell, here perhaps for the first time, may possibly be put to advantageous use in certain structural applications.

In spite of the encouraging note afforded by figure 10 not all applications will be able to use pressurization. Serious gaps still exist in the unpressurized or partially pressurized regions, and these gaps are widening in scope because the shells now being built or contemplated have proportions outside of the range of previous experience; the radius-thickness ratio, for example, may be two to three times as large as those previously encountered. This change will lead to a substantial loss of strength, and experiments are necessary to establish buckling values for this new range of proportions. In addition, the effects of various forms of stiffening on the local buckling of the less dense cylindrical structures have to be considered.

Although the problem of local buckling has here seemingly been given somewhat detailed treatment because of the availability of some interesting new experimental data, it should be borne in mind that the various possible modes of buckling interact in greater or lesser degree and that such interactions may lead to general instability. General instability is, in fact, one of the most important and complex problems facing the structural designer. At the present state of knowledge it is seldom possible to calculate with reasonable accuracy the failure modes, strength, or probability of failure of complex structure, and the uncertainty is expected to increase as the structure becomes less dense, or as high heating rates are introduced. Substantial increase in research work on these aspects of the structures problem is therefore needed.

Another severe problem is that of calculating the temperature distribution, thermal stresses, and thermal deformations in the complex structures that will have to be used. While simple in concept, the procedures become very complex in practice. Some progress has been made in our understanding of the effects of thermal stresses on buckling, but much more remains to be done. Also, a more thorough understanding is necessary of the effects of thermal stresses on ultimate strength.

Structural joints are responsible for a substantial decrease in the efficiency of structures. Additional information is needed on the resistance to failure of various joint configurations. This problem has become of particular importance because of the necessity of attaching additional material of widely different physical make-up for heat protection, and because realistic consideration must be given the problem of designing joints so as to be load-carrying in one direction while stress-relieving in another.

Unusual construction envisioned for spacecraft.- Most of the discussion on structures up to this point has been based on vehicles which must pass through the atmosphere; the consideration of vehicles which are intended solely for outer space travel may lead to radically different and novel structural concepts. Since no precedent exists in the field, ideas on the structural configuration are not firmly defined, but the imagination of those long interested in space has been fertile, however, and has produced many envisionary schemes for spacecraft, most of which have appeared in various periodicals from time to time. Not much can be said concerning purely structural problems but conjecture can be made. The vehicles will operate under conditions of essentially zero gravity; this condition, together with the expense of moving weight into space, will result in extremely "flimsy" structures by our earth-bound standards. The efficient design of such lightly-loaded structures and the problem of introducing concentrated loads into the flimsy shells or membrane structures will require much attention. Serious proposals have been made to ferry such structures into space in collapsed form and then to inflate or expand them. Methods of reinforcing them must be developed and already attention is being given the use of inflated tubes as stiffeners or of using a rigidizing foam as a means of reinforcement.

To give an idea of the possible shape of things to come, reference is made to figure 11. This figure includes vehicles that pass through the atmosphere and those which have been suggested for outer space travel. The sphere on the upper left is an example of an inflatable structure. This particular case is intended as a subsatellite to be used for probing, tracking, and guidance. They are constructed of mylar with an evaporated aluminum coating, and already many sizes have been made, the largest being 100 feet in diameter and weighing only 70 pounds. This is perhaps an example of one of the lowest density structures that can ever be made.

The article at lower left is a man-carrying capsule. Present indications are that it will incorporate both the insulated structure and heat sink approaches in structural design. The example at top center is representative of a hypersonic glider-type vehicle, while at bottom center is depicted a case with low wing loading in which expandible extremely flimsy sail-like wings are intended for use in the very low dynamic pressure and temperature regions of the upper limits of the corridor of flight.

The doughnut-shaped vehicle is representative of the space platforms envisioned, and is a good example of the use of shells of high R/t ratios. The space ship utilizing a large reflector is another example of the possible use of inflatable structures, the reflector serving as a means for collecting solar energy to be used for propulsion purposes. The remaining two space ships - the umbrella-like configuration and the one with wing-like surfaces which have been extended in window-shade fashion - are examples of construction which must use large radiation areas to radiate away internally developed heat, as might be obtained with the use of nuclear propulsion systems.

Thus, it is seen that the structure of space vehicles may take on diverse and weird forms. Problems of transporting, of fabrication, and of erection, and of providing structural stability, as well as the problems previously mentioned of providing heat and radiation protection and of protection against meteor erosion, are innumerable. Our imagination must be prodded to the hilt in the consideration of these problems, and in this connection it seems fitting to quote the following: "The body travels more easily than the mind, and until we have limbered up our imagination we continue to think as though we had stayed at home. We have not really budged a step until we take up residence in someone else's point of view."*

MATERIALS

Number of materials and number of physical properties on an increase.- Until now, aluminum and steel have been the primary materials used in aircraft structures and powerplants, and structural joints have been formed largely through the use of rivets. For present and future hypersonic aircraft and spacecraft construction, however, the materials problem is aggravated by high temperature and consideration is being given to nearly all metals and their alloys, to their oxides, and to a host of diverse materials including refractory materials, ceramics, plastics, and adhesives.

There are, in fact, two striking trends prevalent in the development of materials for structural application: (1) a rapid increase in the types of materials being considered, and (2) a marked increase in the number of physical properties of concern. Figure 12 gives an indication of the growth in number of materials being considered in the past few years, and figure 13 indicates the increase in variety of physical properties of concern.

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*From "The Complete Life" by John Erskine.

The main difficulty with most materials is that while they exhibit desirable properties of one kind they fail in another. Ceramics, for example, while possessing very good heat resistance and insulation properties, are heavy and brittle and possess very poor tensile and shock resistant properties. As another example, most of the present ablating materials work well only for very high heating rates, whereby nearly all the heat is consumed immediately at the surface by the ablating process with very little heat being carried through the material by conduction. For lower heat rates, however, conduction becomes a problem - temperature and thermal stresses occur within the ablation covering with the result that the material cracks, spawls, or falls away in chunks. There are indications that some of the more recent ablation materials may not suffer these faults, but in spite of these hopeful signs, much additional development work is needed, especially to determine when and where this relatively new concept of ablation can best be applied.

Many of the functions essential to successful space flight operation, such as viewing and communication, will also motivate the development of materials. Viewing ports and antennae, as examples, will present specialized problems of development, and related items such as seals and insulators will also be of concern.

As space is penetrated, one of the new problems that must be faced is that of radiation effects from nuclear power plants on structural materials. The problem area is relatively new and not much backlog of experience exists. A few tests have been made in recent years, however, and these indicate that for many materials no reduction in strength is brought about by radiation; indeed, yield stress and ultimate stress are found to increase substantially in these cases, while ductility seems to decrease. In other cases, radiation definitely causes a reduction in strength. Also, since a portion of radiation exposure ultimately appears as heat, there may be instances where strong radiation exposure can develop sufficient heat to raise the temperature of the material to a level where conventional metallurgical effects can occur. Another aspect of concern is the fact that prolonged exposure may make the materials dangerously radioactive.

Problem areas for materials research.- From the foregoing account, it is perhaps evident that materials research applicable to space flight needs to be conducted on an extremely broad front. Not only do the individual properties of concern need to be improved, but materials must be developed in which the several required properties in combination exist at satisfying levels. Until these new or improved materials are developed, available materials will have to be used. Much remains to be done here to supply data needed in design and not now available. The following problem areas may be cited as a general guide to the required research:

1. Extend data on present materials into regions applicable to advanced designs.

2. Develop new improved high-temperature materials through basic research in alloy systems of refractory metals, in the physical chemistry of ceramics, and in adhesives, structural plastics, glazing materials and composite materials.

3. Conduct fundamental research on the physics of solid materials, with the aim of finding and understanding the basic laws that govern deformation and fracture.

4. Increase fundamental research in the chemistry of materials, organic chemistry, chemical reactivity, chemical thermodynamics, and mechanisms of oxidation.

RECOMMENDED RESEARCH ACTIVITY

A discussion such as this on the structures and materials problems of space vehicles should perhaps also give consideration to the research facilities that are needed to help solve the problems. Attention is directed to a rather thorough and detailed paper on high-temperature facilities for structures and materials research that has been prepared for the Structures Panel of this meeting. To avoid duplication, no discussion on facilities will be given herein.

Instead, it is considered fitting to close this paper with recommendations of worthwhile research that may be undertaken in the fields of materials and structures applicable to space technology:

1. Study further the nature of the environment including a more detailed description of the properties and winds of the atmosphere and how they vary diurnally and in position, as well as establishing more definite information on the radiation level and extent of meteor particles in space.

2. Establish levels of the various loads sources, both steady and nonsteady, with a view toward providing rational loads for design.

3. Determine load distribution on components, especially in the hypersonic region where boundary-layer growth and shock wave interactions are governing factors.

4. Further develop the art of designing optimum structural configurations, and of means for constructing nonredundant-type structures (free of thermal stresses), especially when using materials in combination, where problems of bonding and of joints are severe.

5. Develop improved and simplified methods for thermal stress analysis.

6. Develop flutter analysis techniques applicable through the hypersonic range and which include such complicating aspects as high angle of attack, whether involving aerodynamic forces or servo control-structural coupling, and of means for handling forced response problems such as acoustically induced vibration or gust excited motions.

7. Develop better materials of construction, including structural and powerplant materials of higher strengths and higher temperature resistance, insulating and high heat-capacity materials having higher strengths, coatings having better emissive properties and materials with better ablation properties, adhesives of high strength for high-temperature application, and materials and rigidizing foams for use in inflatable or expandable structures.

CONCLUDING REMARKS

This paper has dealt with the broad aspects of the structures and materials problems that will be faced in the design of space-flight vehicles. One of the obvious conclusions drawn is that there are a great many new problems to be solved. This is perhaps to be expected from the tacit thought contained in the paper that while it has taken man some 50 years to reach flight speeds in the order of 1,000 feet per second, he is now trying to bridge suddenly the gap between these speeds and values 25 times as large.

Many of the ideas expressed in this paper are based on real and current problems, some are conceptual. In this regard a final point is to be made: to achieve a realistic structural design of a space-flight vehicle, it is essential to make a sound analysis of the various approaches available. Only by reducing concepts to hard and cold engineering numbers is it possible to tell what can be done, and what cannot be done.

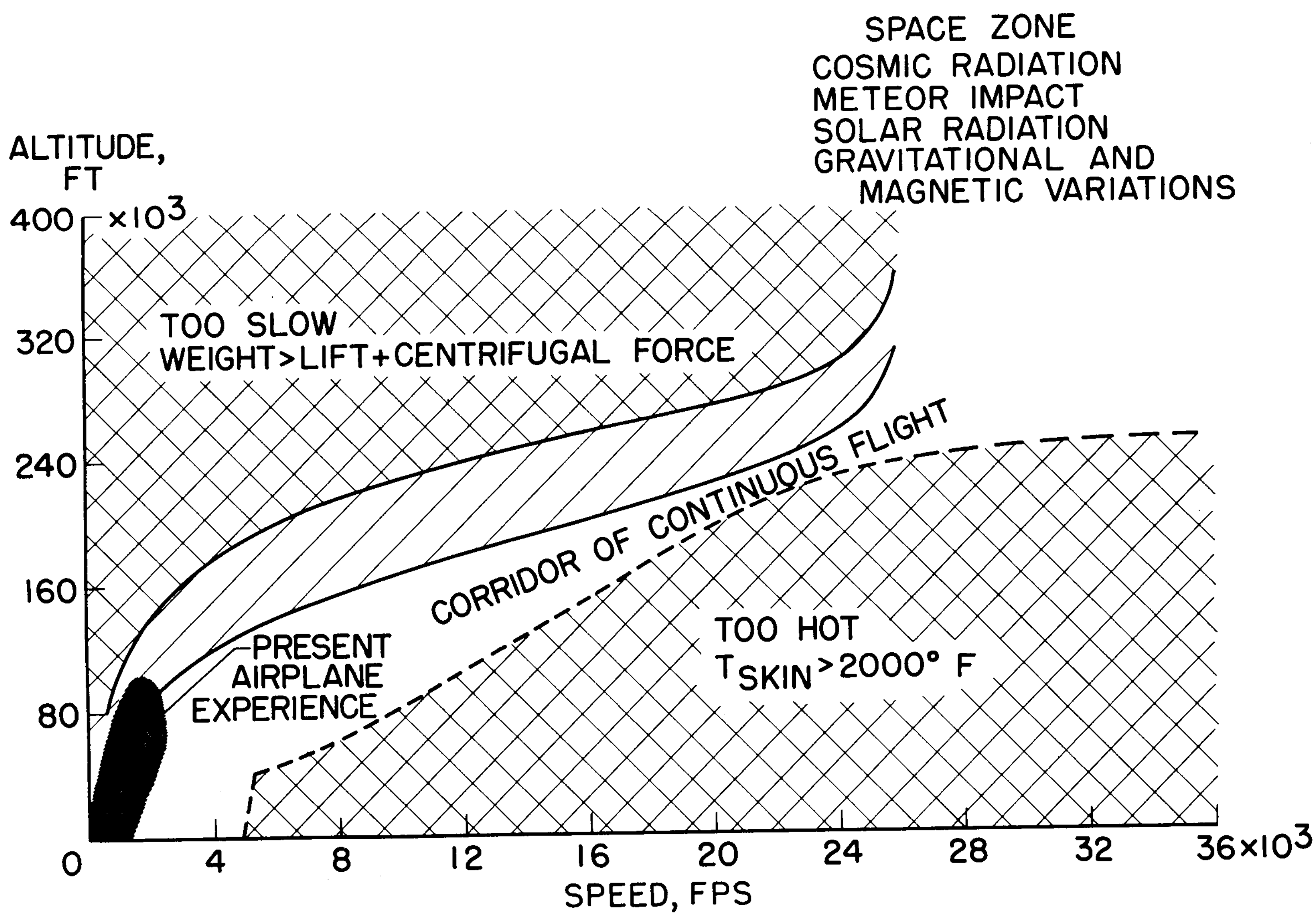


Figure 1.- Regions of flight. NASA

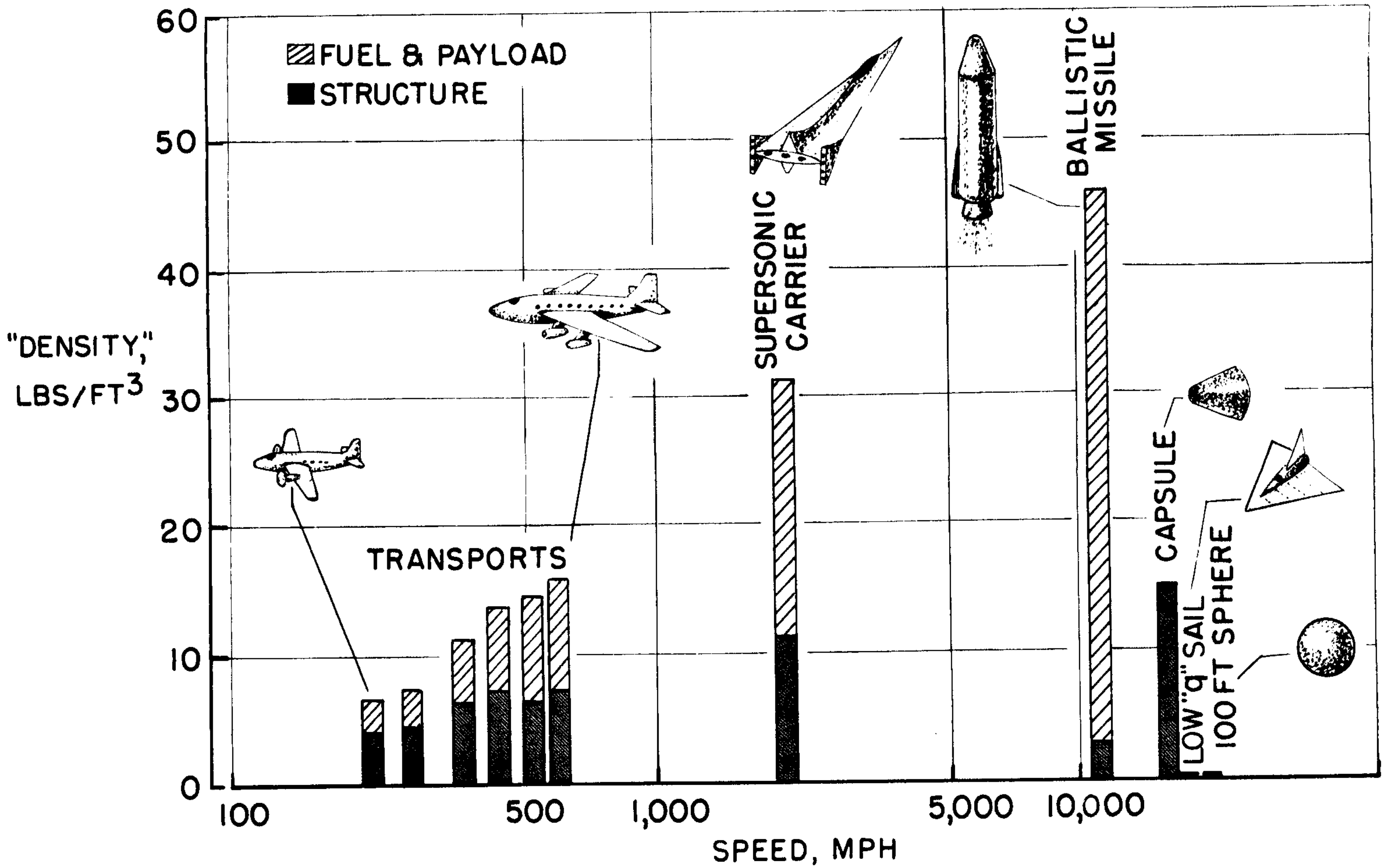


Figure 2.- Structural "density" trends. NASA

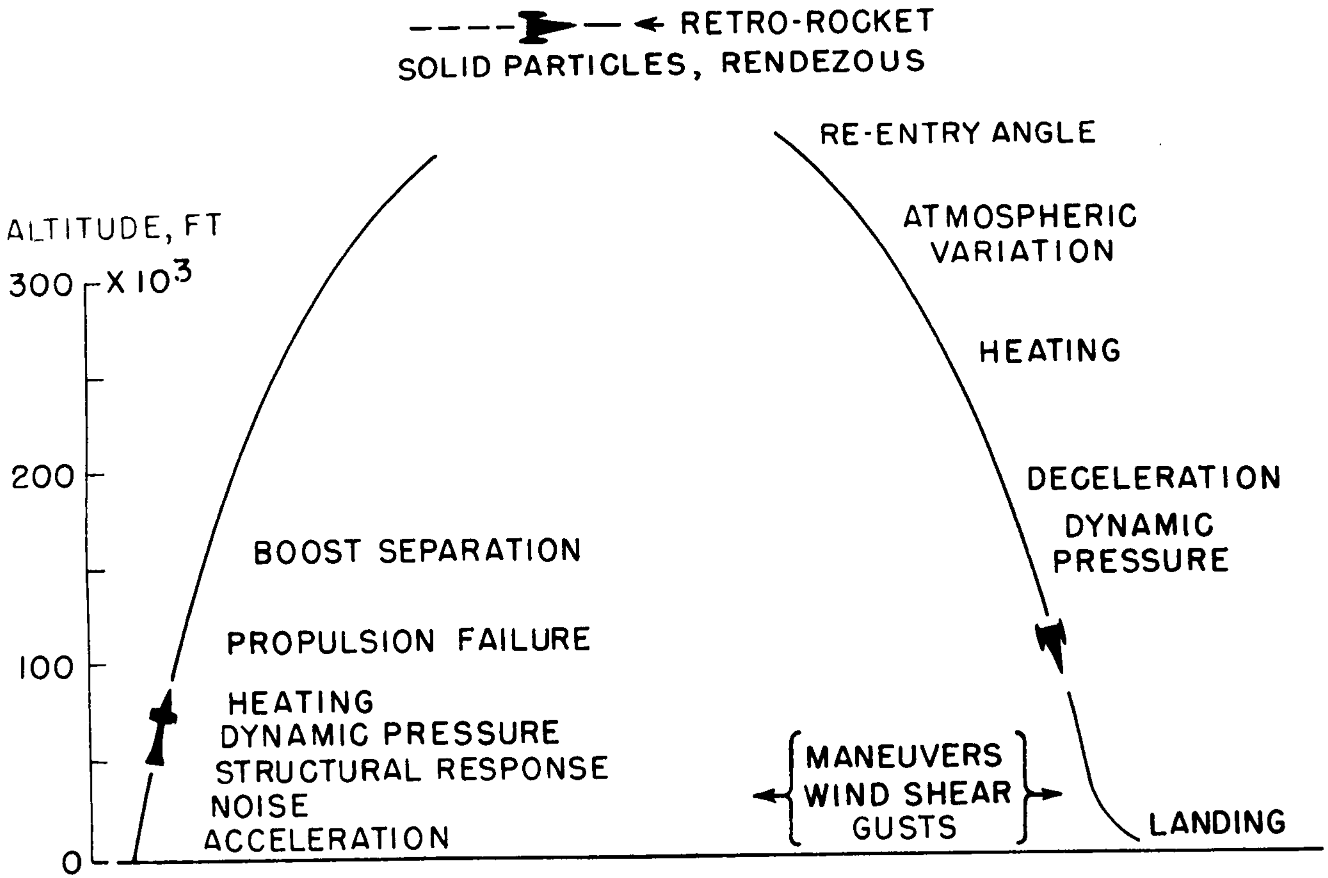


Figure 3.- Load sources. NASA

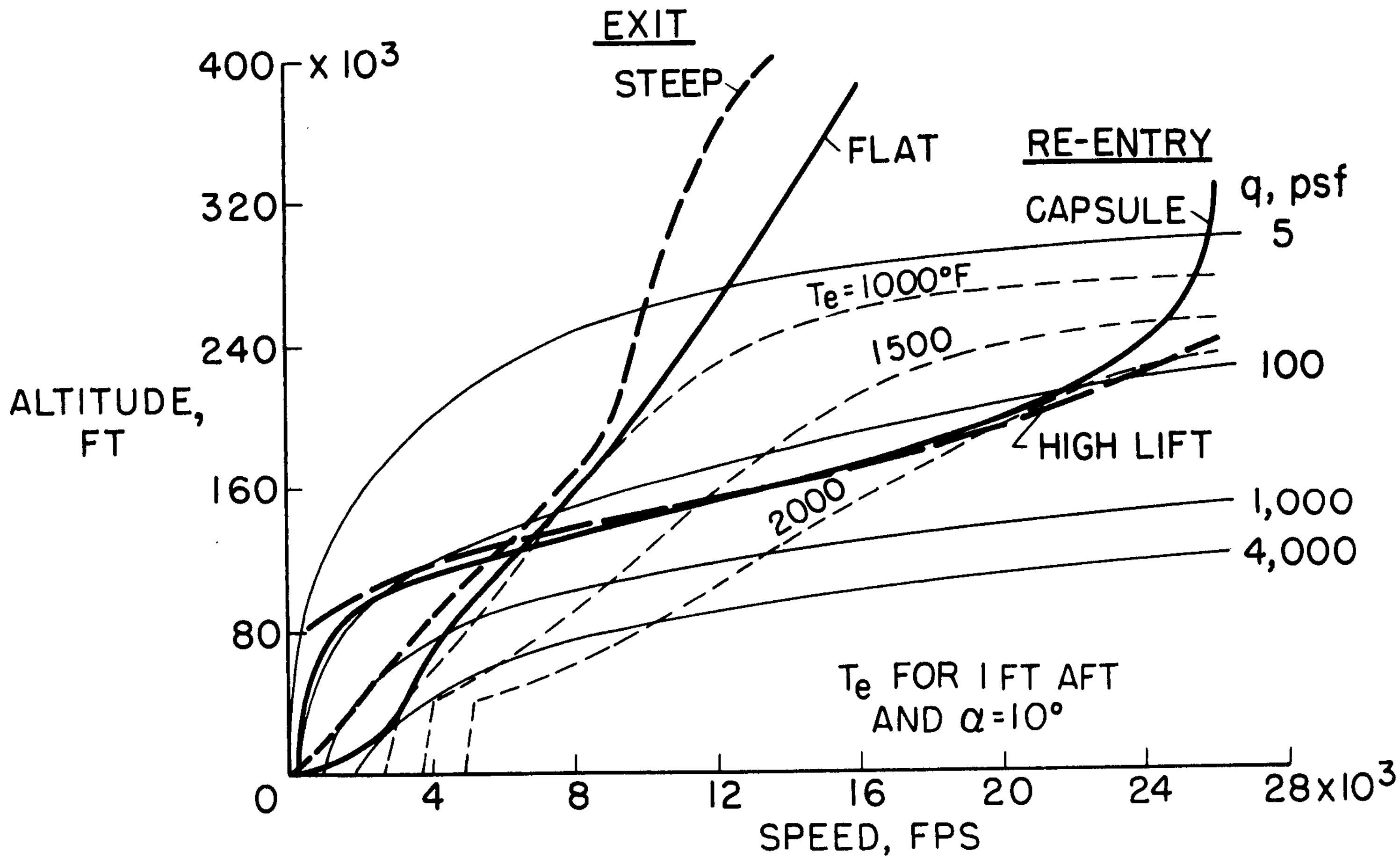


Figure 4.- Temperatures and dynamic pressures during exit and reentry.

NASA

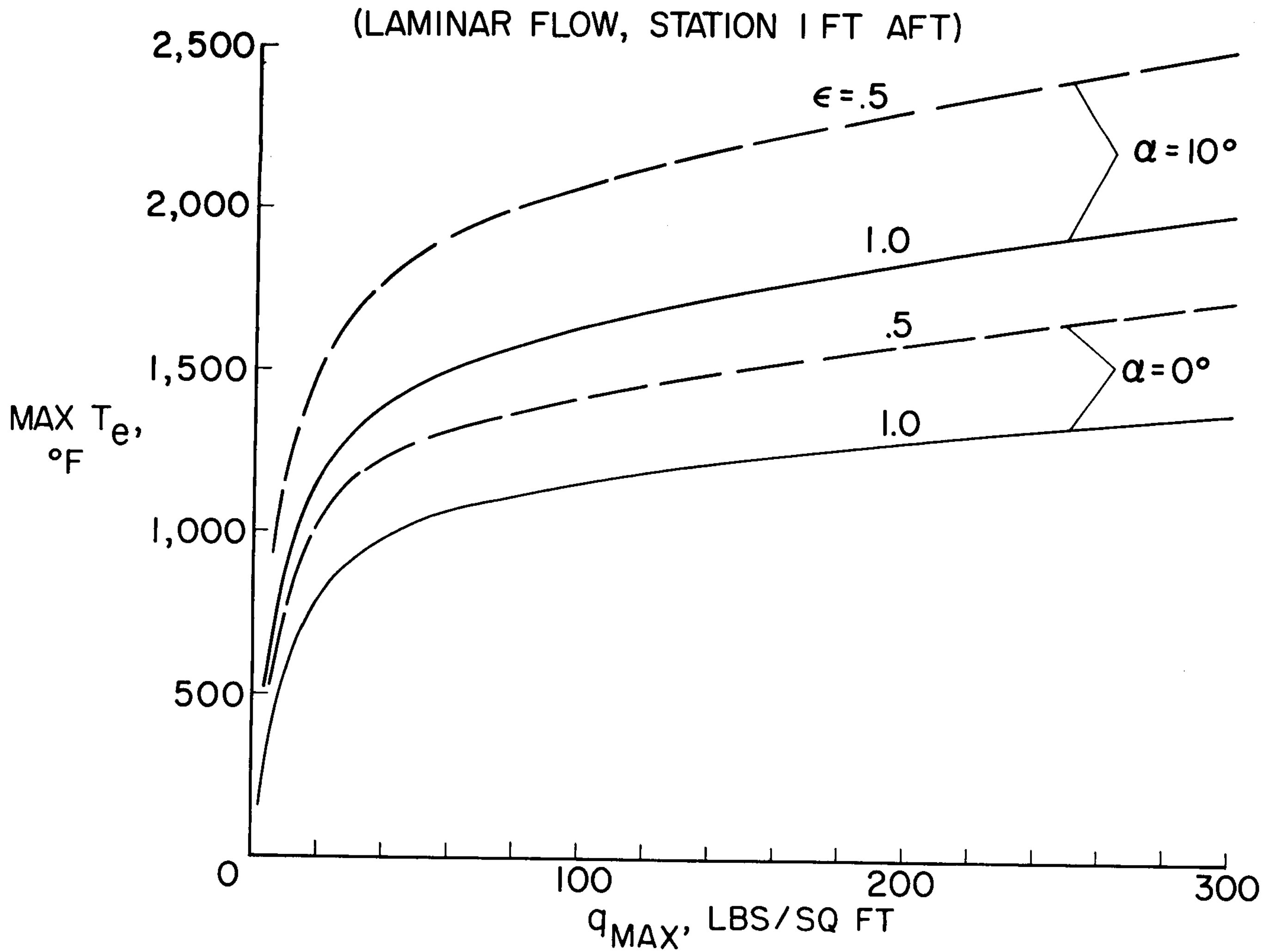


Figure 5.- Effect of angle of attack and emissivity on equilibrium temperatures.

NASA

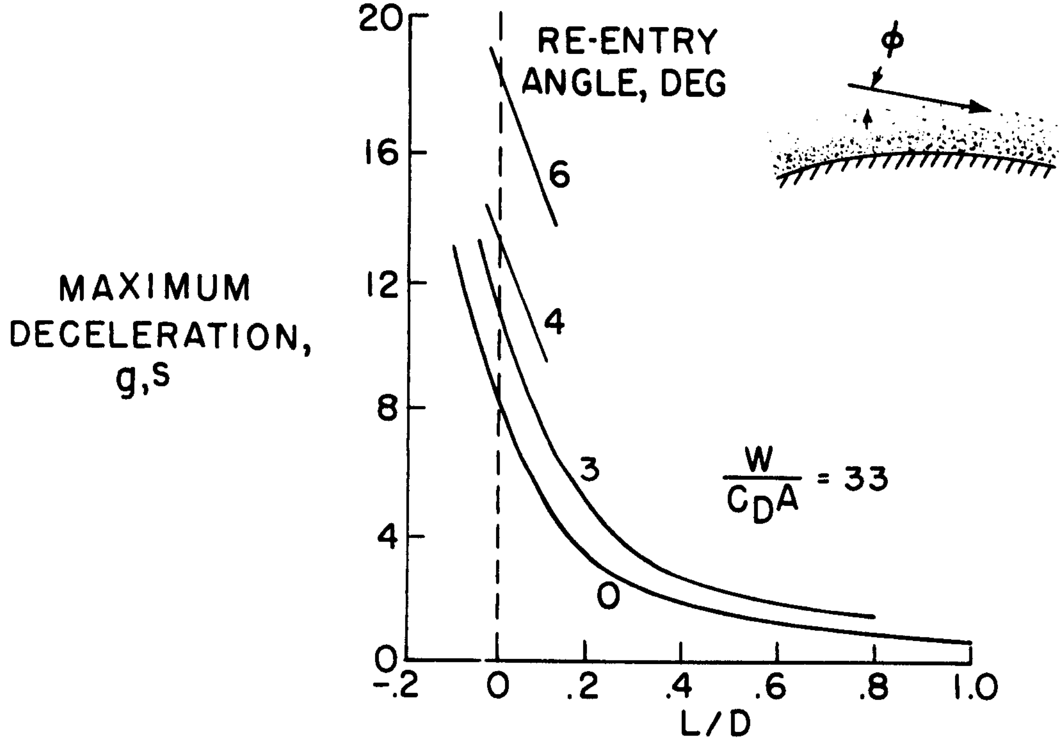


Figure 6.- Effect of reentry angle and L/D on maximum deceleration. NASA

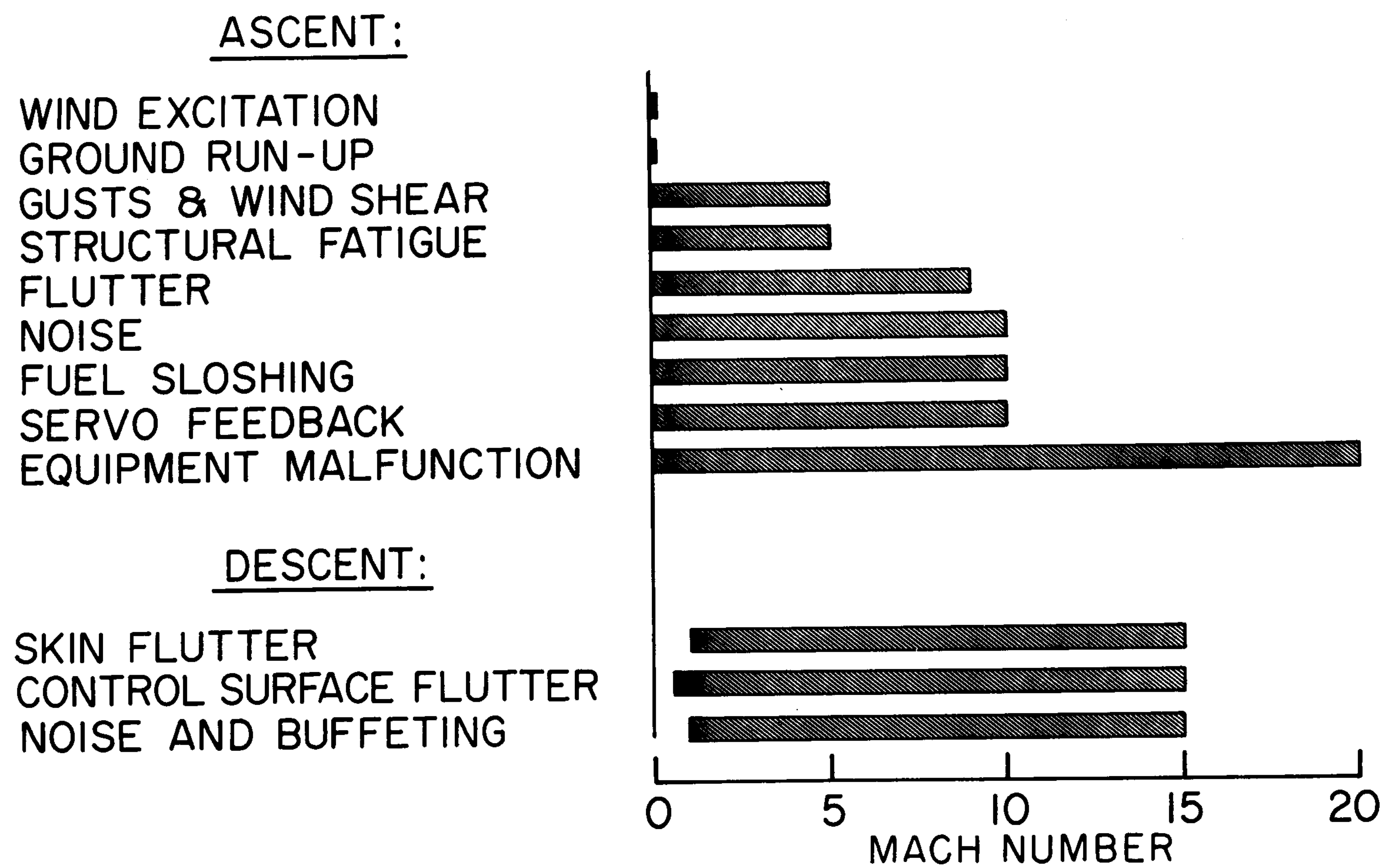


Figure 7.- Mach number range of importance for various dynamic problems. NASA

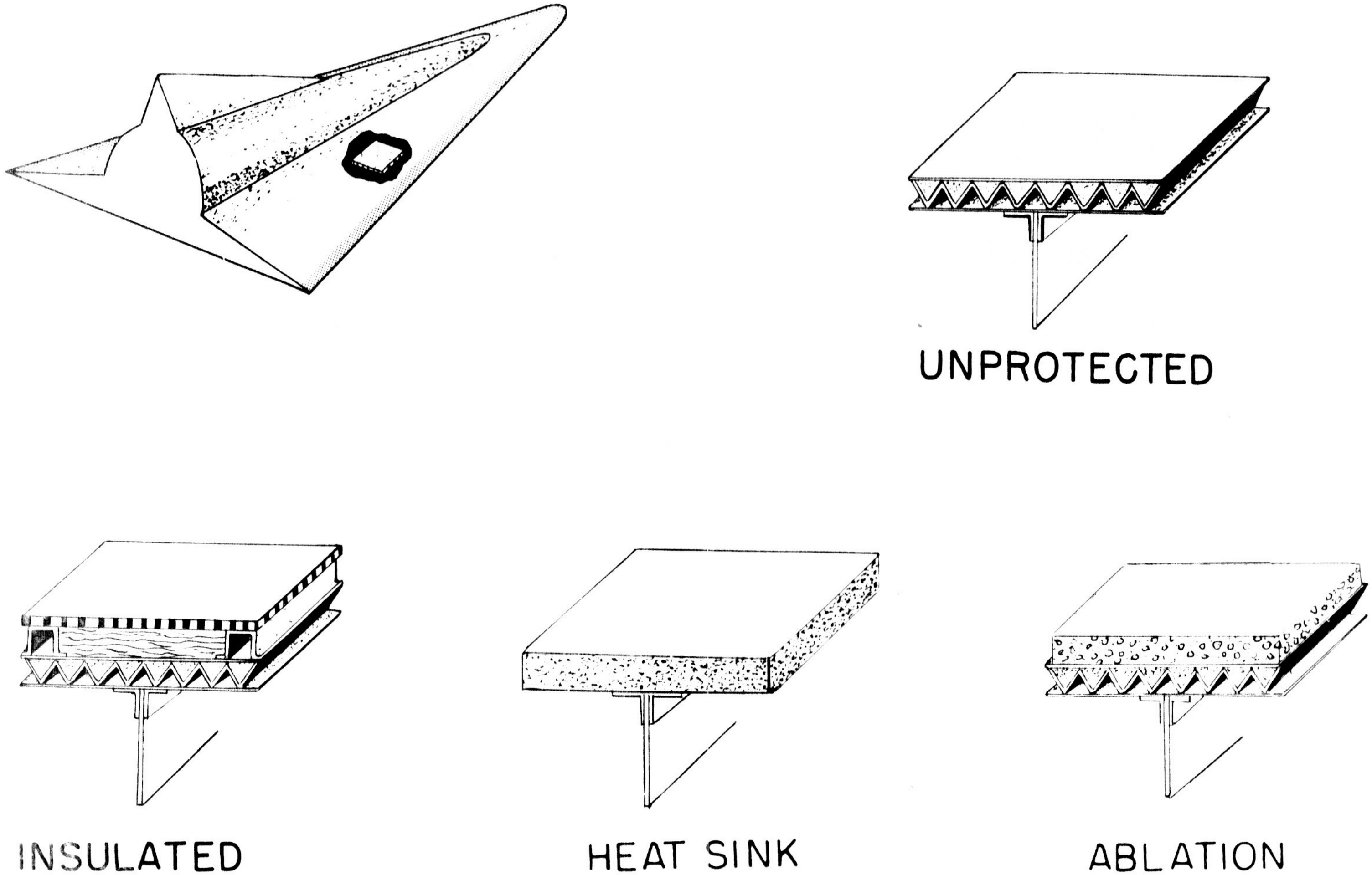


Figure 8.- Structural approaches for wing areas. NASA

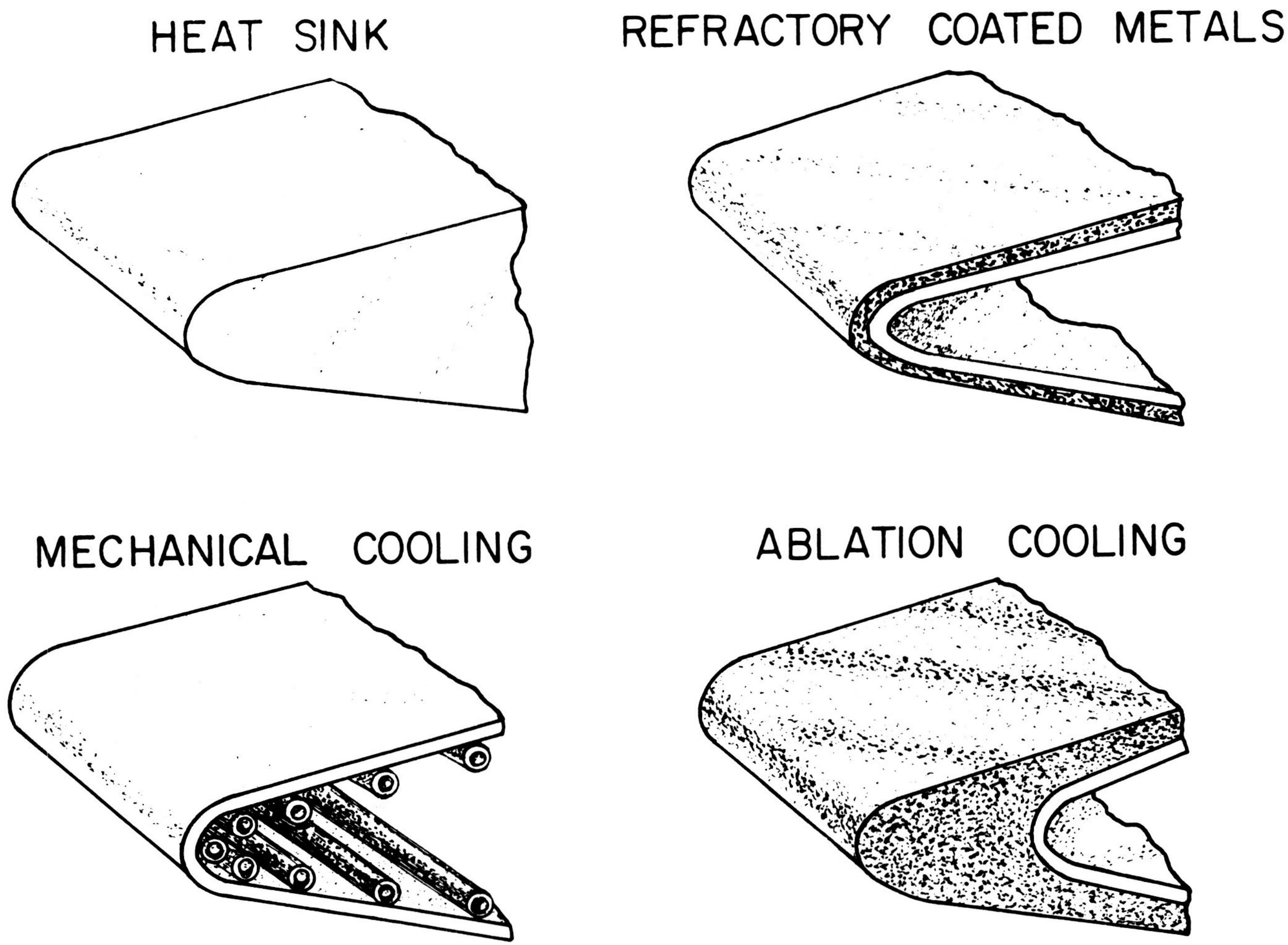


Figure 9.- Leading-edge designs. NASA

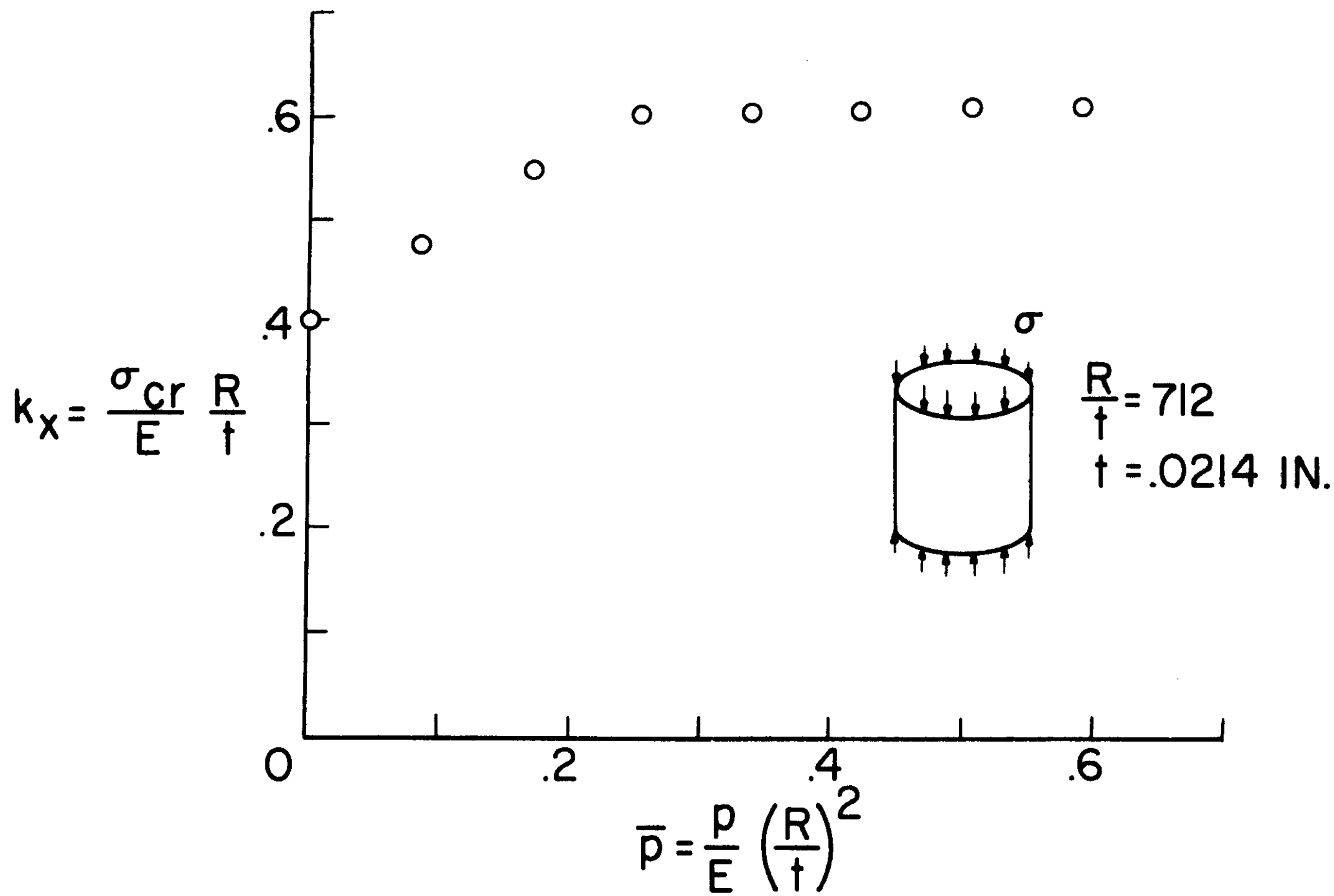


Figure 10.- Buckling coefficient for cylinders with internal pressure. NASA

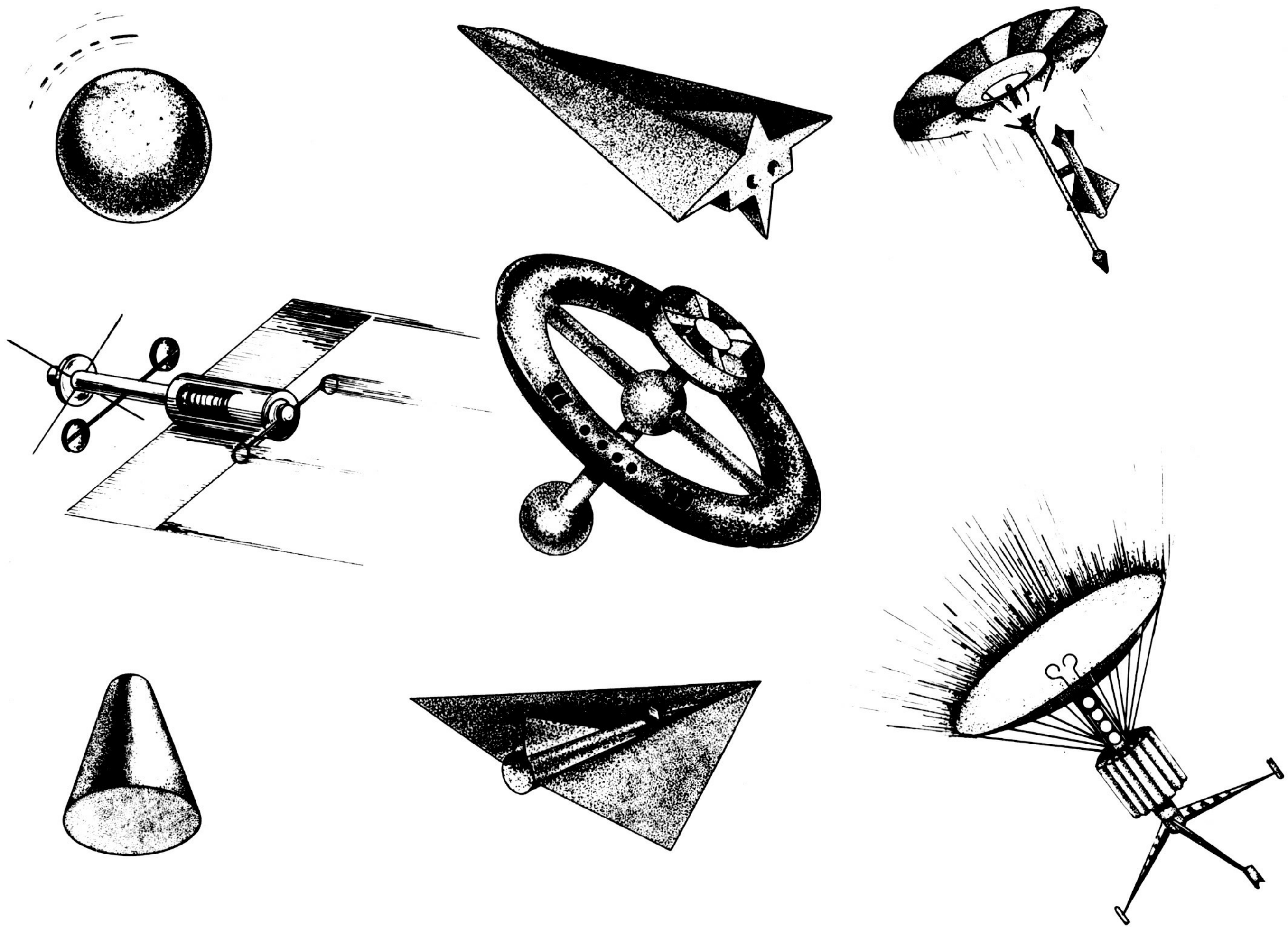


Figure 11.- Vehicles for space flight. NASA

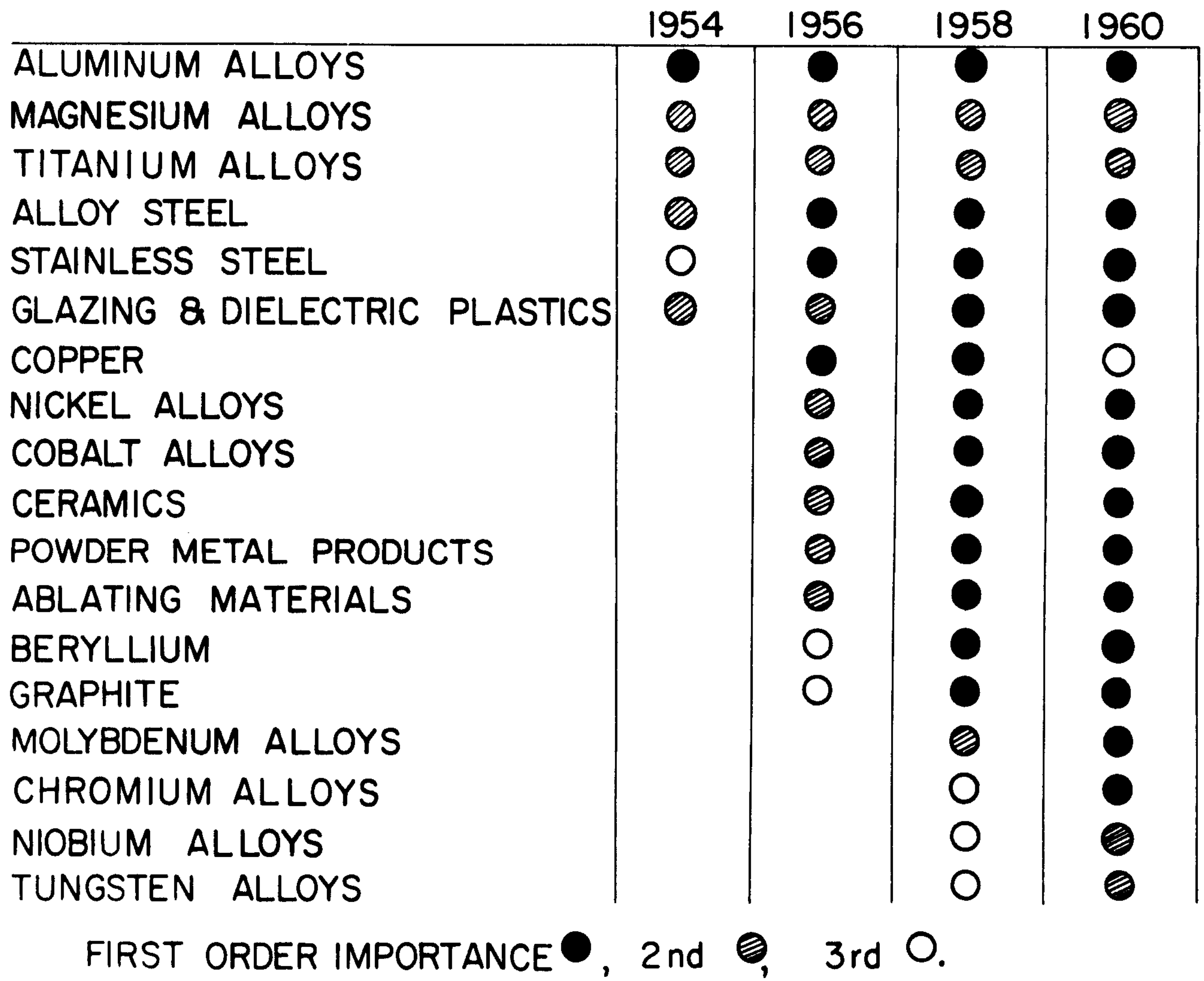
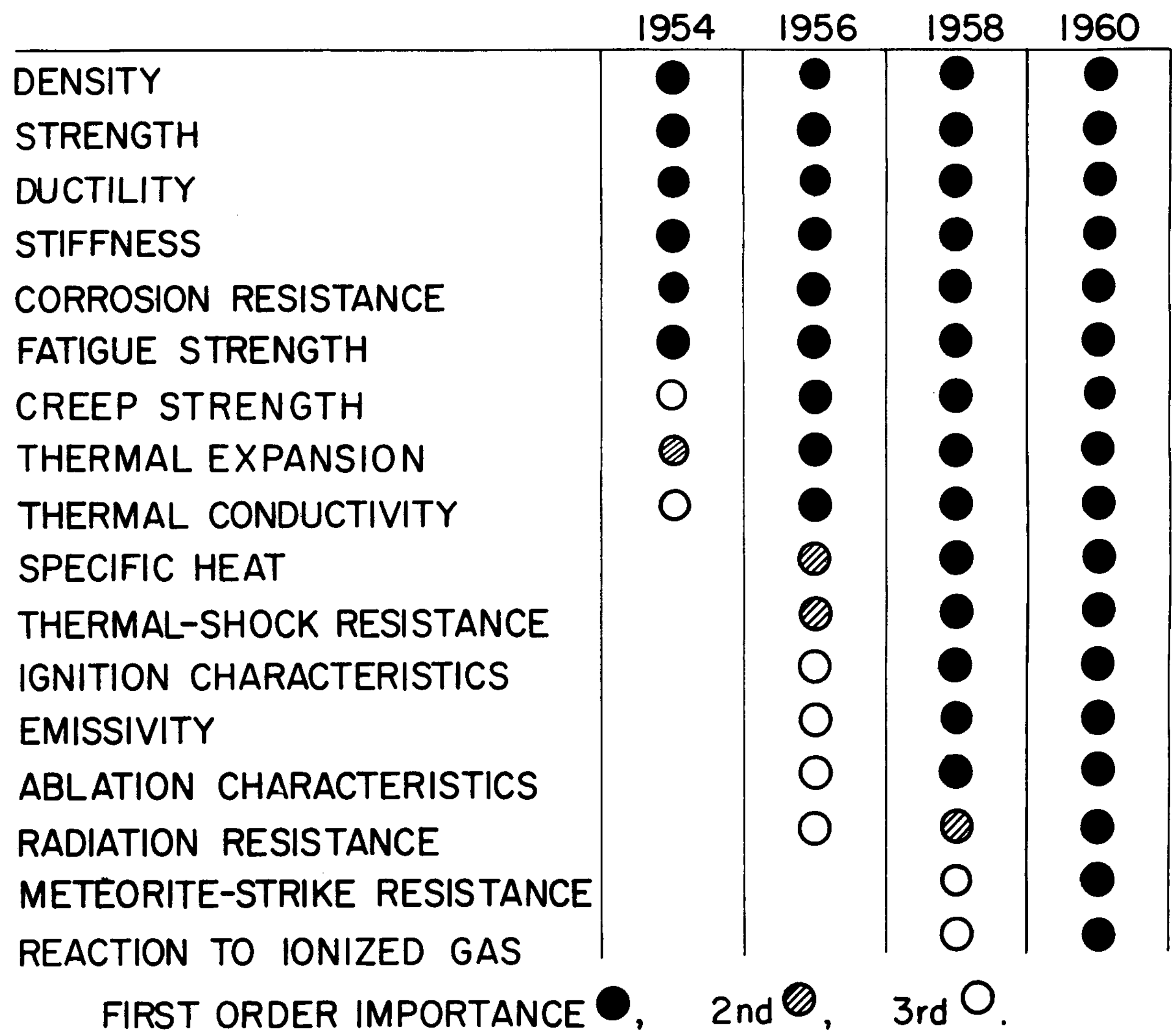


Figure 12.- Materials for use in construction of airplanes, missiles, and spacecraft.

NASA



NASA

Figure 13.- Significant properties of structural materials for airplanes, missiles, and spacecraft.